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Joshua T. West

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High Precision Devices, Inc.
1668 Valtec Lane
Suite C
Boulder, CO 80301 -4655

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14. ABSTRACT
Report developed under topic #A2-3677, contract W911NF-10-C-0004.
High Precision Devices, Inc. has successfully designed, built, tested, and delivered a cryogen free dilution refrigerator for scalable quantum computing. This document is intended to summarize the overall operation and performance of the cryostat. Also included (as Appendix 1) is the delivery and installation documentation provided with the refrigerator.

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Report Title

Dilution Refrigerator Technology for Scalable Quantum Computing

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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TOTAL:

Number of Papers published in peer-reviewed journals:

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Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

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This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

1 a. University of California - Santa Barbara

1 b. 3227 Cheadle Hall
3rd floor, MC 2050
Santa Barbara CA 931062050

Sub Contractor Numbers (c): SB110086
Patent Clause Number (d-1): Exhibit C
Patent Date (d-2): 7/8/11 12:00AM
Work Description (e): Assist development of technical specifications; participate in design reviews; provide adv
Sub Contract Award Date (f-1): 7/8/11 12:00AM
Sub Contract Est Completion Date(f-2): 8/5/12 12:00AM

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1 a. University of California - Santa Barbara

1 b. Office Of Research
Cheadle Hall, Room 3227
Santa Barbara CA 931062050

Sub Contractor Numbers (c): SB110086
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Inventions (DD882)

Scientific Progress

Technology Transfer

HIGH PRECISION DEVICES, INC.

Final Report p09027-0001 US Army

Contractor: High Precision Devices, Inc. (HPD)

Contract No. W911NF-10-C-0004, CLIN 0002

Requisition/Purchase Request/Project No. 55222PHST209323

Period of Performance: June 23, 2010 – August 6, 2012

Prepared by Josh West, May 8, 2014

Abstract

Report developed under topic #A2-3677, contract W911NF-10-C-0004.
High Precision Devices, Inc. has successfully designed, built, tested, and delivered a cryogen free dilution refrigerator for scalable quantum computing. This document is intended to summarize the overall operation and performance of the cryostat. Also included (as Appendix 1) is the delivery and installation documentation provided with the refrigerator.

The following are items of progress made since the last progress report:

- Assembly and testing at HPD completed.
- To improve low temperature performance, it was determined that we needed greater pressure in the returning 3He line, i.e. more impedance before the still, in order to liquefy the returning 3He at the 2nd stage of the PT.
- ^{3}He return impedance was optimized to achieve the necessary flow rate and reduce the heat load on the still.
- Initial cooling of the cryostat from room temperature was augmented with a liquid nitrogen loop. This reduced the time required to cool from 300 K to 4 K from ~40 hours to ~14 hours.
- Base temperature of the dilution refrigerator was measured to be less than 15 mK. However, an exact determination of the base temperature was not possible with existing thermometry.
- Cooling power was measured to be within 80% of the manufacturer's specification of 200 µW when used in a "wet" system. This is considered to be excellent.
- Temperature control of the cryostat during operation was very stable.
- The cryostat was shipped to UCSB and installed in the laboratory there. The cryostat performance after installation was identical to the performance at HPD.

Percentage of completion of study topics:

Development of CAD representing cryostat:	100%
R&D of He3 system loop:	100%
Development of high density wiring:	100%
Design of Gas Handling System	100%

This document is intended to summarize the performance and operation of the cryogen free dilution refrigerator built by High Precision Devices, Inc. and delivered to Dr. John Martinis at the University of California at Santa Barbara under an STTR grant provided by the US Army.

The final result of this STTR is a high-performance dilution refrigerator specially designed for quantum computing experiments. The cryostat has been delivered and is currently installed and operating in the lab at UCSB. The performance of the cryostat has been independently confirmed by the end user at UCSB.

1. The cool down

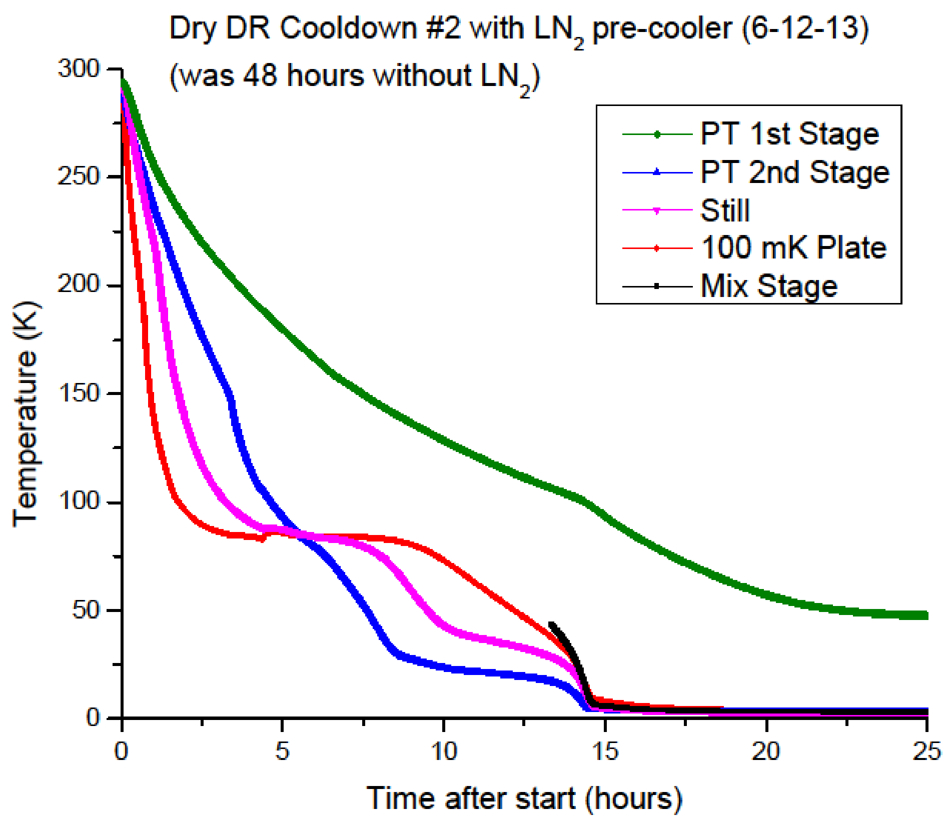


Figure 1. Cooling the cryostat from room temperature using the liquid nitrogen cooling loop. The stage plates are cooled to <4 K in ~14 hours (versus ~48 hours with conductive cooling only).

The addition of a liquid nitrogen pre-cooling loop was necessary to facilitate cooling from room temperature to <4 K in a reasonable amount of time.

2. Condensing the mixture

After using a small amount of the mixture for leak checking we condensed the remaining mixture slowly (~2 hours) while circulating. Although we were condensing at a slow to moderate pace, we never needed to elevate the back pressure above 1 bar. It appears that we will not require a separate compressor in the gas handling system. This is a crucial detail because the helium compressors used in other cryogen-free dilution refrigerator systems are notoriously unreliable. The failure of this compressor puts the cryostat's valuable ^{3}He supply in jeopardy.

3. Dual input impedance

The initial design of the ^{3}He circulation loop included a low temperature valve allowing for parallel impedances. It was thought that a lower impedance loop would be necessary for condensing the ^{3}He/^{4}He mixture in a reasonable amount of time and for pre-cooling the lower DR stages. After several cool downs we came to the conclusion that even though the secondary impedance did reduce the amount of time necessary to condense the mixture, it was not significant enough to make it worth the added complexity and the addition of possible leak paths. With the return pressure less than 1 bar, it takes ~90 minutes to completely condense the mixture.

4. Normal circulation

In normal circulation using the turbo pump we had the following steady state temperatures and pressures:

Still: 0.6-0.7 K (with 2-2.5 mW of still heater power)
100 mK heat exchanger stage: 120 mK
Mixing Chamber: <15 mK
Still pumping line pressure: 0.3 mbar
He-3 return pressure: 600 mbar

The fridge operated well with no oscillations in temperature or pressure. The fridge temperature and all pressures were stable with no operator intervention and constant heat loads. The cryostat operation was not highly sensitive to either the still level, ^{3}He/^{4}He mixture ratio, or still heater power.

5. Power Curve

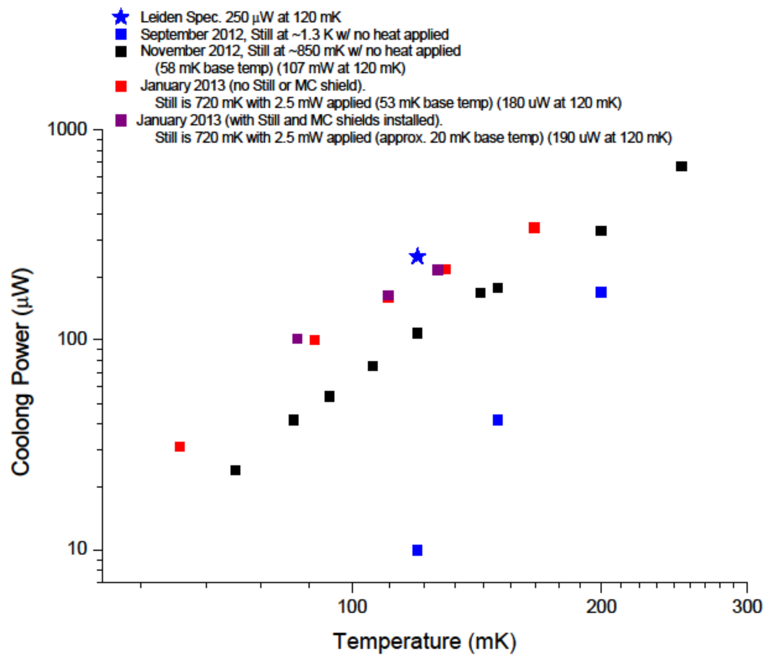


Figure 2. Dilution refrigerator power curve showing steady improvement in the cooling power as the impedance kept adjusting closer to the ideal value.

Figure 2 shows the cooling power as a function of mixing temperature (the "power curve"). We have obtained ~80% of the manufacturer's specification for cooling power (250 µW at 120 mK). The 250 uW number is obtained using a "wet" system with a 1 K Pot operating at ~1.5 K. This "dry" cryostat is instead condensing the ^{3}He using the cooling from the pulse tube at ~2.7 K. Therefore, the total cooling power is necessarily reduced.

6. Thermometry

Millikelvin thermometry is notoriously difficult. The mixing chamber thermometer that was supplied with the dilution refrigerator was uncalibrated and came with only a "generic" curve. We attempted to cross calibrate this thermometer using a Lakeshore RuOx thermometer that was calibrated down to ~50 mK. In addition, we were able to cross reference to a Lakeshore Cernox sensor calibrated to ~80 mK. This proved to be unsatisfactory so we set out to calibrate the mixing chamber thermometer using a primary standard that we borrowed from a researcher at NIST. This standard was composed of a CMN thermometer and a set of superconducting fixed point devices. We successfully used the fixed point devices to cross-check the resistive thermometers. Unfortunately, having only twisted pair wires and no coaxial lines installed in the cryostat, we were unable to get a high enough sensitivity on the CMN thermometer to obtain reliable data at low temperature.

The convolution of all of the thermometers yielded a base temperature of <15 mK. Our best estimate is that the actual base temperature was between 11-13 mK, but definitely less than 15 mK. This is

excellent performance considering the fact that we are converting a wet system to operate cryogen-free and the huge surface area that increases our blackbody heat load.

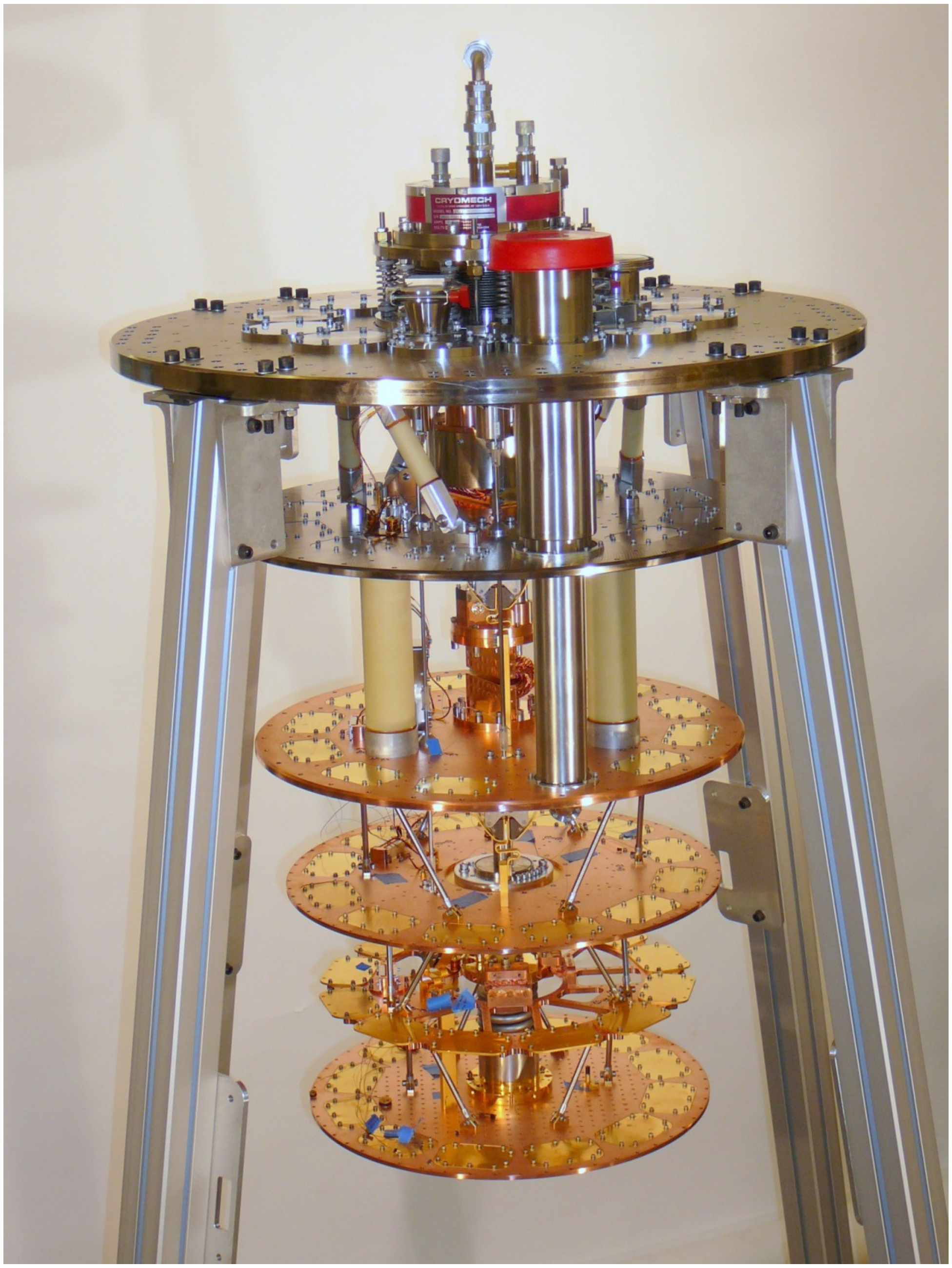


Figure 3. Assembled dilution refrigerator at HPD (with radiation shields and vacuum jacket removed)

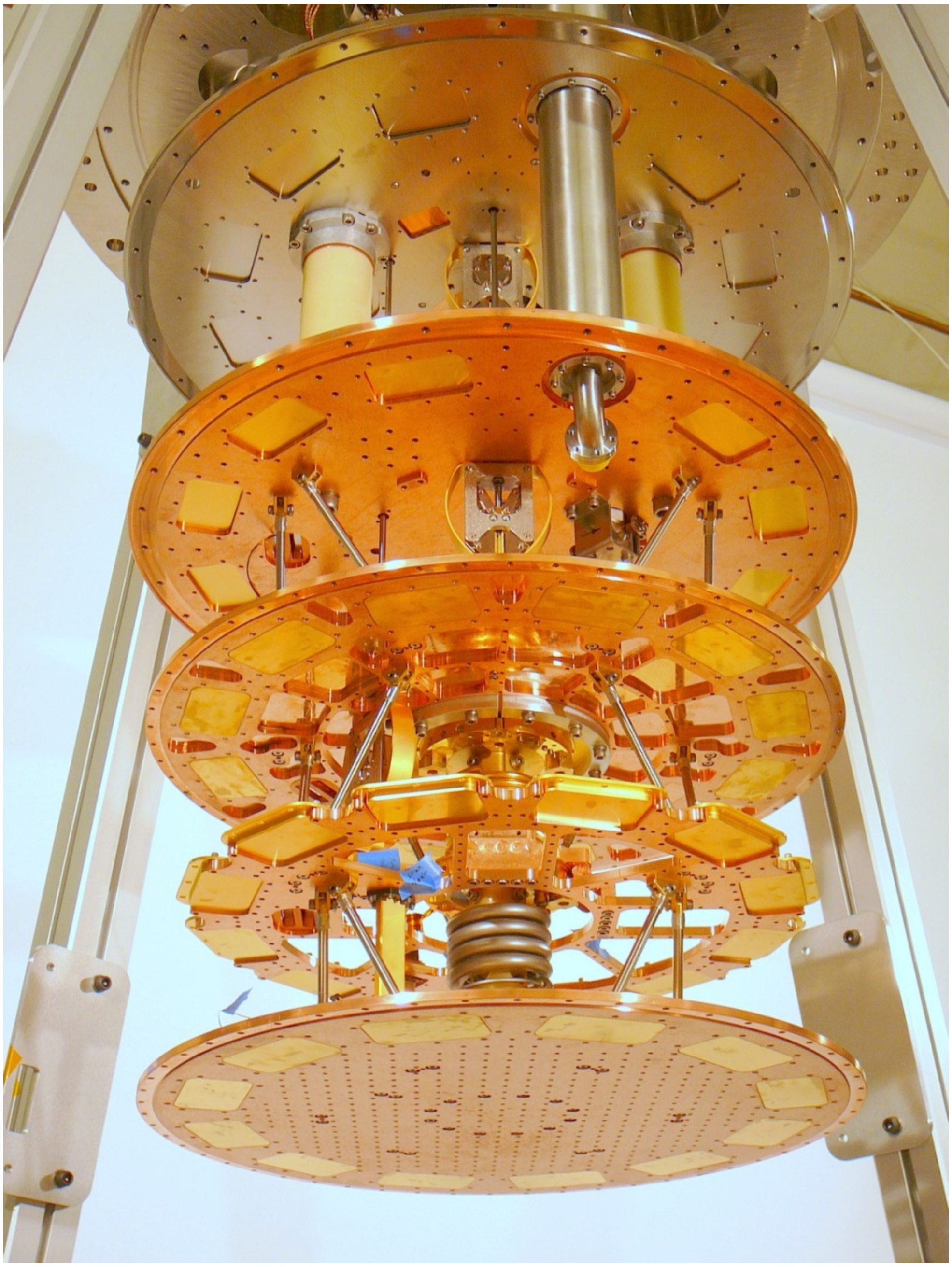


Figure 4. View of the dilution refrigerator cold stage from below. Note the symmetric ring of wiring feed-through ports for high-density wiring.

Conclusions

We are very pleased with the performance of the cryogen free dilution refrigerator and we believe that this will prove to be an invaluable tool for continuing research in the field of quantum computing. Going forward, we have determined that the liquid nitrogen precooling loop is essential to the practical operation of the cryostat. We have also found ways of reducing the complexity of the overall system without impacting the performance that will result in increased reliability and lower cost.

Appendix 1

This document is intended to list the items that were purchased under the Army STTR contract and will be transferred to UCSB at the conclusion of testing. We will also try to identify items that UCSB will need to procure or have ready for the installation of the dry DR cryostat.

1. Cryomech pulse tube compressor

   Note: The compressor for the PT415 system is much larger than the compressor used with your ADR cryostats. The compressor should have a dedicated 50 A breaker and it requires 3 GPM of cooling water. The compressor is also physically larger. The spec sheet is here: http://www.cryomech.com/specificationsheet/PT415RM_ss.pdf

2. Remote Valve motor

   We have the motor mounted on a stand (not included). I think you had mentioned mounting it from the ceiling. It could be mounted inside of the Faraday cage but we did not do this for vibration concerns.

3. 90 degree Aeroquip fitting

This elbow can be used (or not) depending upon where you decide to mount the remote valve motor. I would recommend keeping the fitting because the pulse tube head impedance was tuned with this fitting in place.

4. Gas ballast tanks

We have them mounted inside of the Faraday cage

5. Gas handling system

Everything in this picture is included (main GHS panel, two pressure switches, three digital pressure gauges with three PDR2000 gauge readers, nitrogen trap, nitrogen Dewar)

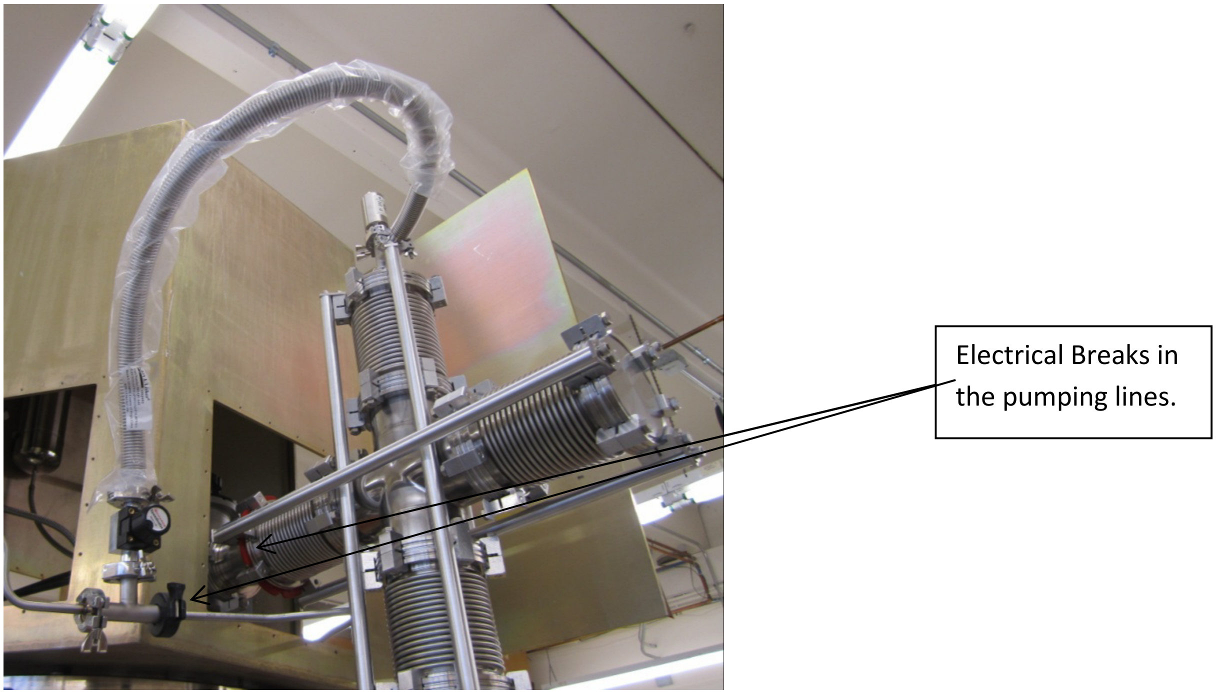
6. Backing pumps

Two Edwards XDS10 dry pumps plus two KF25 bellows valves.

Note: The two flexible pumping lines attached to the pump on the right belong to HPD. Two KF25 bellows 1 meter long will go with the cryostat (one from the turbo outlet to the GHS and one for the GHS to the inlet of the backing pump). You will need a new line to go from the outlet of the circulation pump to the GHS.

7. Turbo pump system

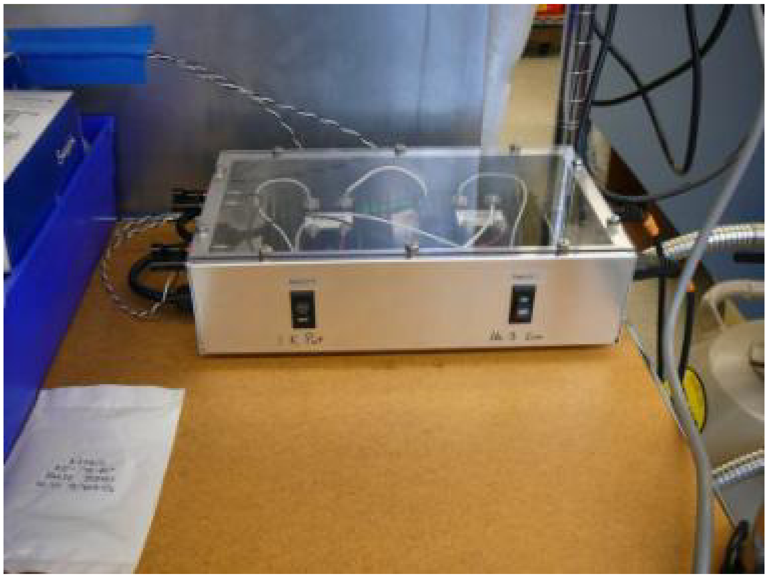
Starting from the cryostat there is: ISO80 bellows sealed right angle valve, 80 to 100 ISO adapter, ISO 100 bellows cross (with 10 torr vacuum gauge on top), 100 to 160 ISO adapter, Edwards turbo pump and controller (Note: We are not planning to send the stand that the turbo pump is mounted on).



We added a Tee and valve so that you can use the turbo to pump on both sides of the impedance. Also, note the two electrical breaks.

8. ISO 160 ‘U-tube’ (given to HPD by NIST)

9. Backing pump relay box



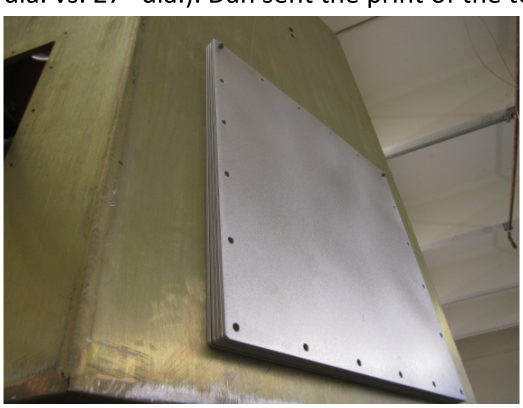
We were planning on keeping this relay box to test cryostats in the future. I would assume that you may want to do something a little more 'permanent' like you have on the other two DR systems.

10. Two helium dumps (130 liter volume each) with He-3/He-4 mixture

We made custom hard lines to go from the GHS to the dumps. It is quite unlikely that these lines will work for your installation.

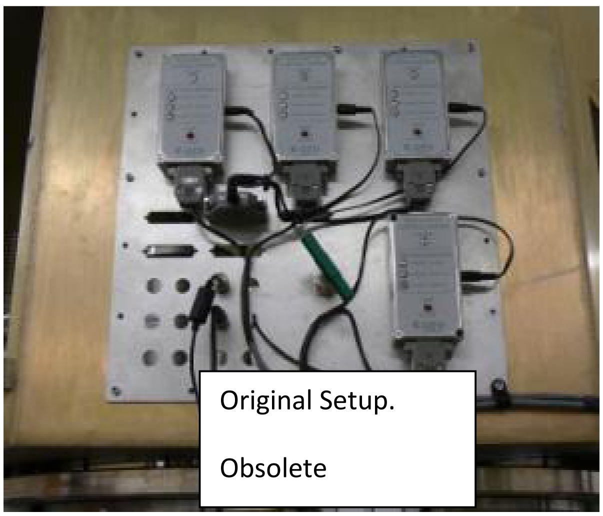
11. Cryostat test stand and faraday cage

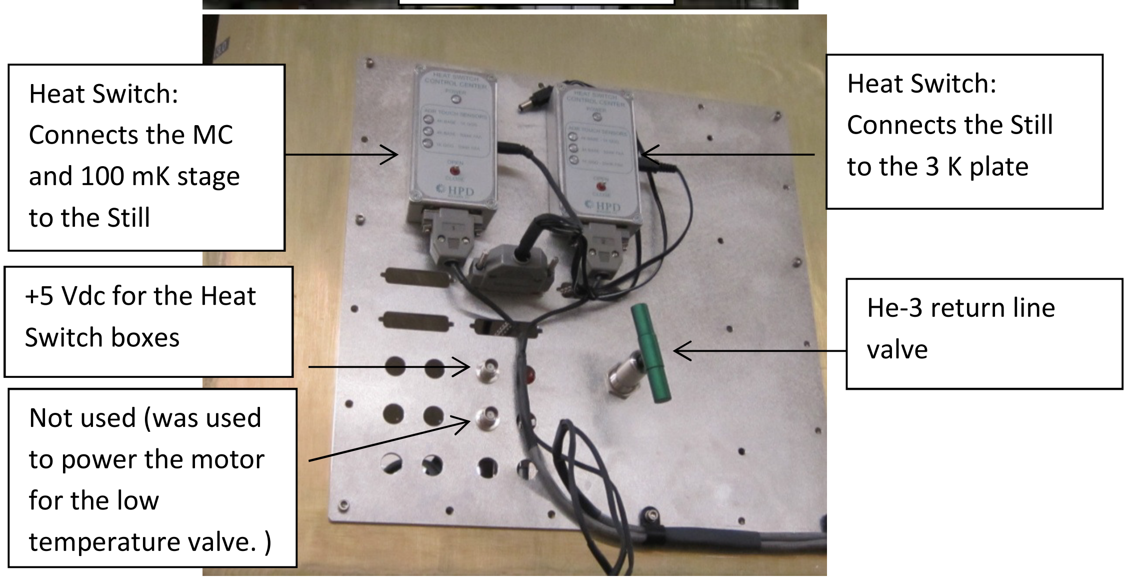
We were not planning on sending the test stand because it is our understanding that you will make another three-leg stand with Newport air legs (plus, this was never intended to be used for a permanent installation, only testing). We will send the Faraday cage (with the front door).
Please note that the 300 K plate is larger on this cryostat than on your two wet DR cryostats (30" dia. vs. 27" dia.). Dan sent the print of the top plate to use for dimensions when making the stand.



We are including 5 blank panels for the Faraday cage that you can modify as needed.

12. Heat switch panel

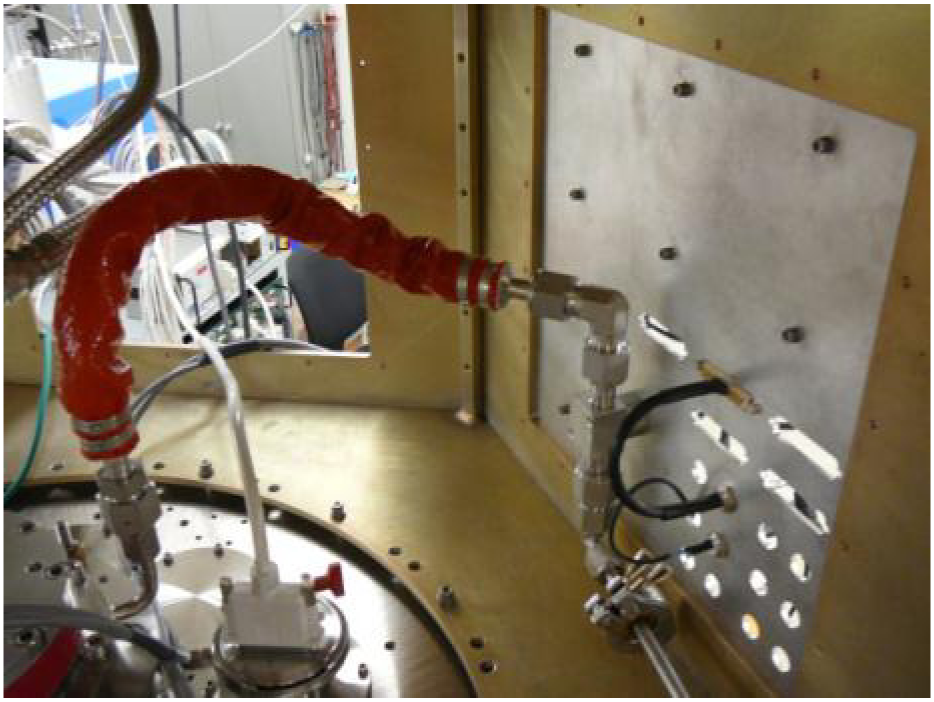




The three top heat switch boxes control the three mechanical heat switches. The lower box controls the low temperature valve. All four boxes are powered from a 12 VDC power supply (the upper BNC cable). At the moment we are running the motor for the low temperature valve by manually

controlling the power to the motor with a variable power supply. We need to reprogram the control box for it to run the valve properly.

The valve for the He-3 return line is also mounted to this panel.



Back side of H.S. panel.

13. Cryostat Vacuum gauges and valves

The KF40 valve on the left will go with the cryostat. The valve on the right (mounted from the KF50 port) belongs to HPD. The vacuum gauges mounted to the tee also belong to HPD. The cryostat will <u>not</u> include any gauges for monitoring the cryostat vacuum.

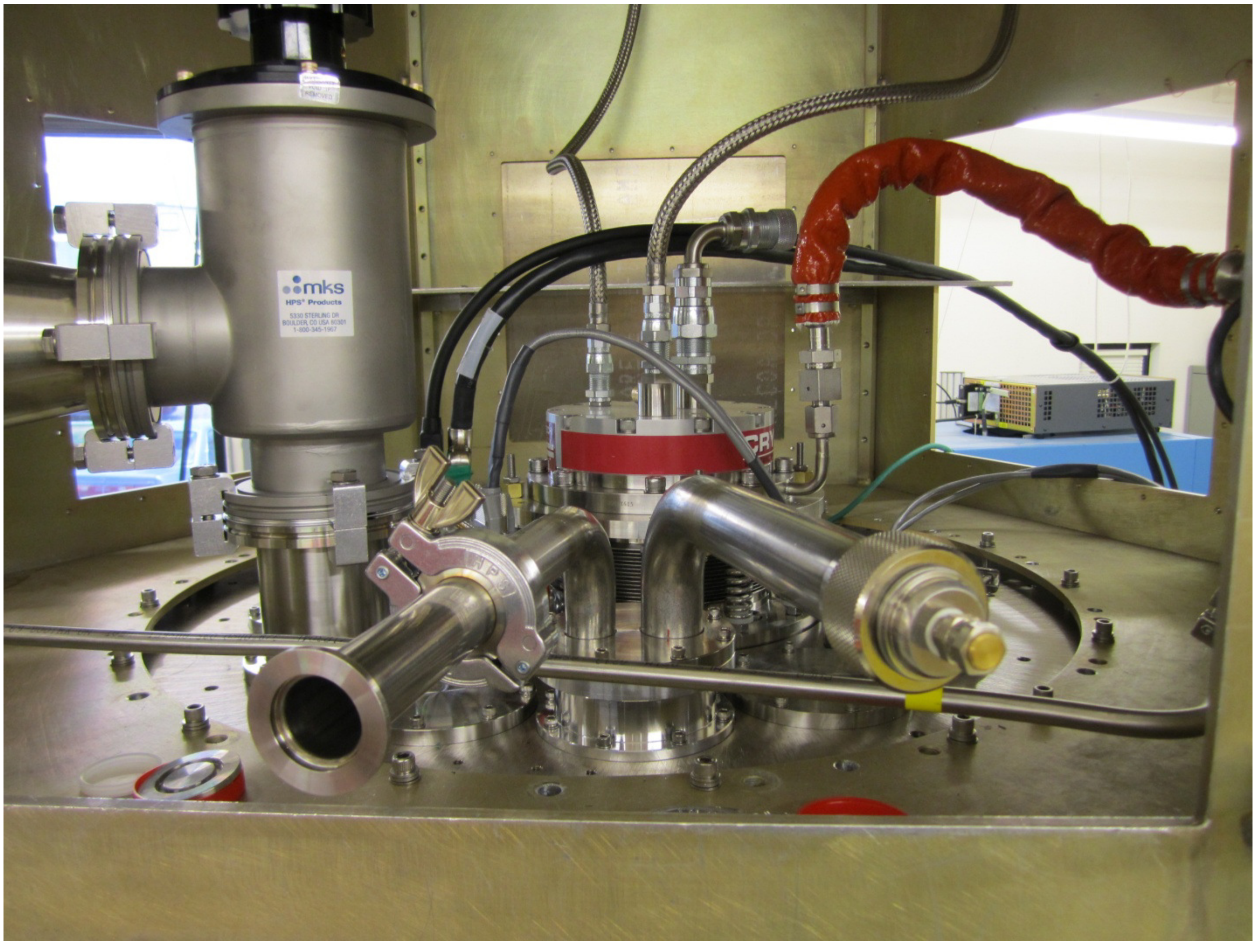
14. Wiring feed though flanges

The two dual-25 pin feed through connectors on the left (between the pulse tube and the valve for the still) are staying with the cryostat. The two DB-25 cables on the left carry all of the cryostat RuOx, diodes, and heaters. The custom cable on the third DB-25 port is for the heat switch motors and the touch indicators (we need to discuss these). The fourth connector is completely open. There is a short section with a 25 pin micro-d connector mounted to the underside of the 300 K plate for you to connect to.

The third feed through (bottom right) is only temporary while we outfit the cryostat with some extra thermometry for troubleshooting and characterization.

The two documents below are the wiring diagrams for the fridge. It is possible that things will change as we continue testing. I will send an updated version when the cryostat ships that contains the 'as delivered' wiring scheme.

15. Liquid Nitrogen cool down loop



The LN2 loop works identically to the two rapid cool down ADR cryostats that we delivered to UCSB recently.

Cryostat wiring diagram

Heat Switch Wiring

16. Cryostat external wiring

    With the exception of the custom cable going to the heat switch panel, none of the external cryostat wiring or instrumentation (cables, power supplies for the heaters, resistance bridges, diode readers) will be included with the cryostat.

17. Spare Parts

We made a few extra blank port covers. There are three stainless blanks for 300 K, one 300 K port cover bored for welding in a KF50 weld stub, three aluminum rectangular port covers for 50 K, one gold plated copper blank rectangular port, and six small rectangular adapters (two dual micro-d adapters, two single micro-d adapters, and two blanks).